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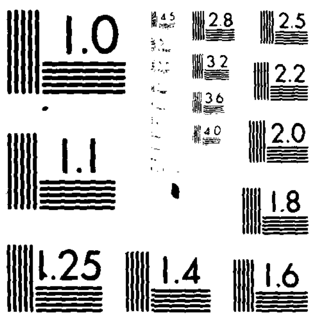

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MX SITING INVESTIGATION

GRAVITY SURVEY - MULESHOE VALLEY

NEVADA

Prepared for:

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Ballistic Missile Office (BMO)
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14 September 1981

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This valley was studied for purpose of making a geologic interpretation which includes estimates of shape of structural basin, thickness of alluvial fill + location of faults.

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FOREWORD

Methodology and Characterization studies during Fiscal Years 1977 and 1978 (FY 77 and 78) included gravity surveys in 10 valleys, five in Arizona, two in Nevada, two in New Mexico, and one in California. The gravity data were obtained for the purpose of estimating the gross structure and shape of the basins and the thickness of the valley fill. There was also the possibility of detecting shallow rock in areas between boring locations. Generalized interpretations from these surveys were included in Ertec Western's (formerly Fugro National, Inc.) Characterization reports (FN-TR-26a through e).

During the FY 77 surveys, measurements were made to form an approximate 1-mile grid over the study areas, and contour maps showing interpreted depth to bedrock were made. In FY 79, the decision was made to concentrate on verifying and refining suitable area boundaries. This decision resulted in a reduction in the gravity program. Instead of obtaining gravity data on a grid, the reduced program consisted of obtaining gravity measurements along profiles across the valleys where Verification studies were also performed.

The Defense Mapping Agency (DMA), St. Louis, was requested to provide gravity data from their library to supplement the gravity profiles. For Big Smoky, Hot Creek, and Big Sand Springs valleys, a sufficient density of library data was available to permit construction of interpreted contour maps instead of just two-dimensional cross sections.

In late summer of FY 79, supplementary funds became available to begin data reduction. At that time, inner zone terrain corrections were begun on the library data and the profiles from Big Smoky Valley, Nevada, and Butler and La Posa valleys, Arizona. The profile data from Whirlwind, Hamlin, Snake East, White River, Garden, and Coal valleys, Nevada, became available from the field in early October 1979.

A continuation of gravity interpretations was incorporated into the FY 80 and 81 programs, and the results are being summarized in a series of valley reports. Reports covering Nevada-Utah gravity studies are being numbered "E-TR-33-" followed by the abbreviation for the subject valley. In addition, more detailed reports of the results of FY 77 surveys in Dry Lake and Ralston valleys, Nevada, were prepared. Verification studies were continued in FY 80, and gravity studies were included in the program. DMA continued to obtain the field measurements, and there was a return to the grid pattern. The interpretation of the grid data allows the production of contour maps which are valuable in the deep basin structural analysis needed for computer modeling in the water resources program. The gravity

interpretations will also be useful in Nuclear Hardness and Survivability (NH&S) evaluations.

The basic decisions governing the gravity program are made by BMO following consultation with TRW, Inc., Ertec Western, and the DMA. Conduct of the gravity studies is a joint effort between DMA and Ertec Western. The field work, including planning, logistics, surveying, and meter operation is done by the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC), headquartered in Cheyenne, Wyoming. DMAHTC reduces the data to Simple Bouguer anomaly (see Section A1.4, Appendix A1.0). The Defense Mapping Agency Aerospace Center (DMAAC), St. Louis, Missouri, calculates outer zone terrain corrections.

Ertec Western provides DMA with schedules showing the valleys with the highest priorities. Ertec Western also recommended locations for the profiles in the FY 79 studies with the provision that they should follow existing roads or trails. Any required inner zone terrain corrections are calculated by Ertec Western prior to making geologic interpretations.

TABLE OF CONTENTS

LIST OF APPENDICES

LIST OF FIGURES

TABLE OF CONTENTS (cont.)

LIST OF DRAWINGS

1.0 INTRODUCTION

1.1 OBJECTIVE

Gravity data from Muleshoe Valley were studied for the purpose of making a geologic interpretation which includes estimates of the shape of the structural basin, the thickness of the alluvial fill, and the location of concealed faults. The estimates will be useful in modeling the dynamic response of ground motion in the basin and in evaluating ground-water resources.

1.2 LOCATION

Muleshoe Valley is located in east-central Nevada about 40 miles (64 km) west of the Utah border and 80 miles (129 km) south of the town of Ely by U.S. Route 93 (Figure 1).

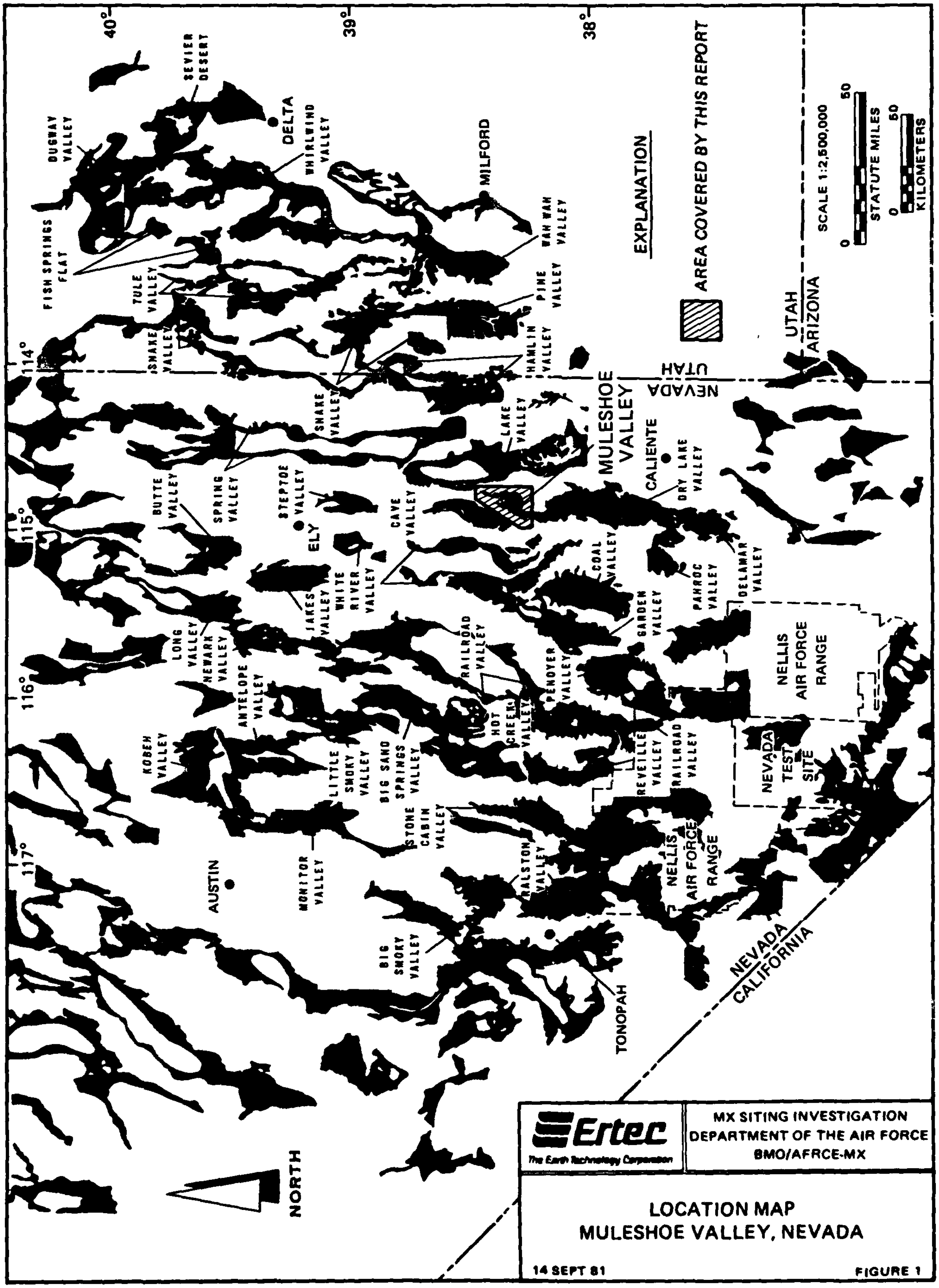
Muleshoe Valley lies between Lake Valley and Cave Valley and opens southward into Dry Lake Valley. Muleshoe Valley is bounded on the west by the southern Schell Creek Range and on the east by the Fairview Range, Grassy Mountain, and Dutch John Mountain (Figure 2).

The area covered by this report lies between North latitudes 38°05' and 38°30' and West longitudes 114°35' and 114°50'.

1.3 SCOPE OF WORK

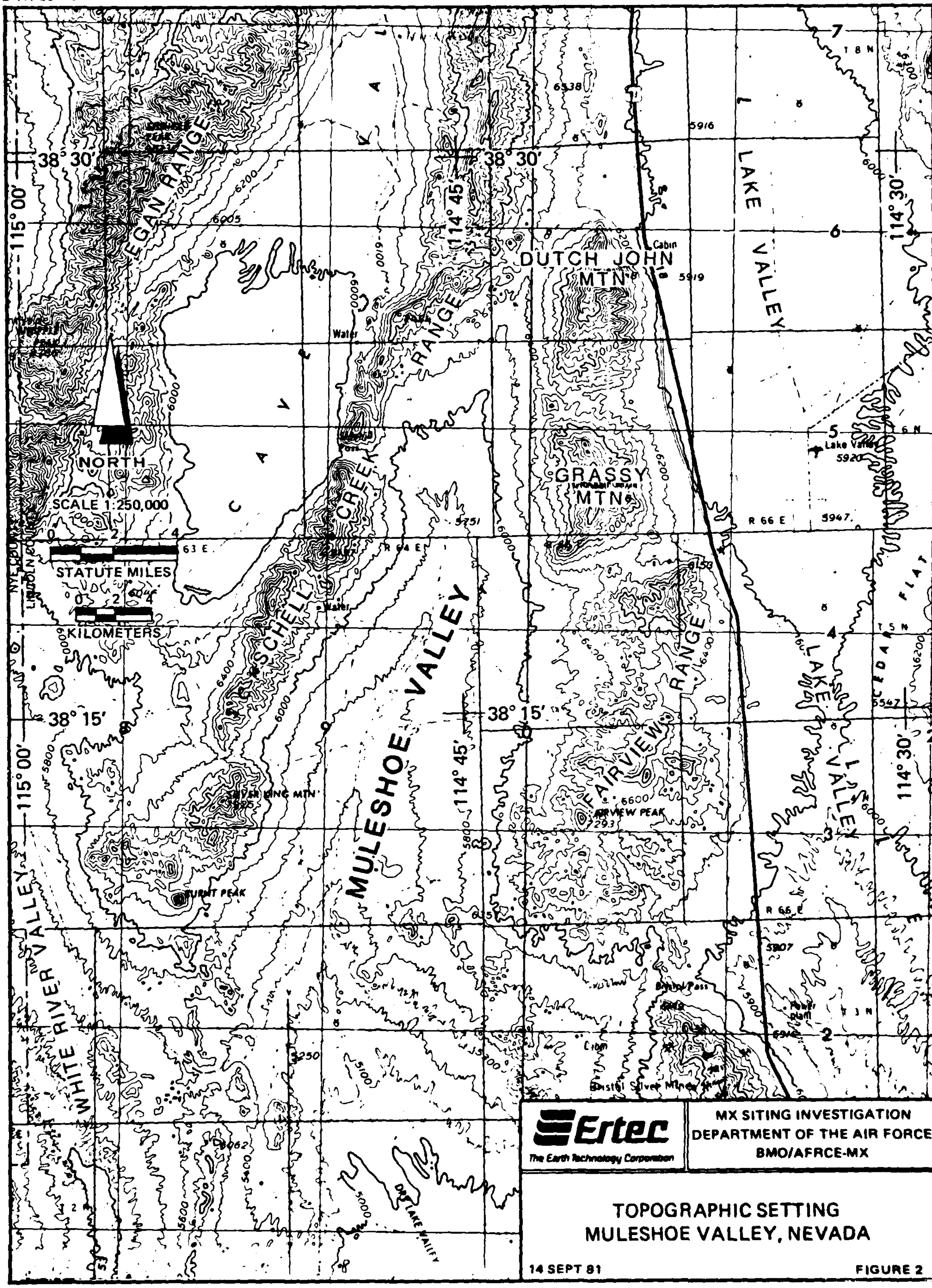
Five primary work elements were completed during this study. They are:

1. Computation and merging of terrain corrections;
2. Synthesis of regional and valley-specific geological data;
3. Evaluation of the regional field and separation of the residual field;



LOCATION MAP
MULESHOE VALLEY, NEVADA

FIGURE 1



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TOPOGRAPHIC SETTING
MULESHOE VALLEY, NEVADA

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FIGURE 2

4. Inverse modeling to estimate depth to bedrock; and
5. Interpretation of structural relationships.

The gravitational field within Muleshoe Valley was defined by data from 224 stations. The distribution of stations is shown in Drawing 1.0 and the station data are listed in Appendix A2.0. The Defense Mapping Agency Aerospace Center (DMAAC) supplied 86 gravity stations from its library, and 138 new gravity measurements were made by the Defense Mapping Agency Hydrographic-Topographic Center/Geodetic Survey Squadron (DMAHTC/GSS).

Muleshoe Valley and Cave Valley were studied together, with the results presented in separate reports. The rectangular region between North latitudes 38°05' and 38°45' and West longitudes 114°35' and 115°00' contains both of the valleys and surrounding mountains. All of the 522 gravity stations within this region were used to establish a common regional trend for the two valleys. Following separation of the residual field, the geologic modeling of the two valleys was done independently.

2.0 GRAVITY DATA REDUCTION

DMAHTC/GSS obtained the basic observations for the new stations and reduced them to Simple Bouguer Anomalies (SBA) as described in Appendix A1.0. Up to three levels of terrain corrections were applied to the new stations to convert the SBA to the Complete Bouguer Anomaly (CBA). Only the first two levels of terrain corrections described below were applied to the library stations.

First, the DMAAC, St.Louis, Missouri, used its library of digitized terrain data and a computer program to calculate corrections out to 104 miles (167 km) from each station. When the program could not calculate the terrain effects near a station, Ertec Western used a ring template to estimate the effect of terrain within approximately 3000 feet (914 m) of the station. The third level of terrain corrections was applied to those stations where relief of 10 feet (3 m) or more was observed within 130 feet (40 m). In these cases, the elevation differences were measured in the field at a distance of 130 feet (40 m) along six directions from the stations. These data were used by Ertec Western to calculate the effect of the very near relief.

The CBA values and principle facts for the Muleshoe Valley stations are listed in Appendix A2.0.

3.0 GEOLOGIC SUMMARY

Muleshoe Valley is a small valley in the eastern part of the Great Basin section of the Basin and Range physiographic province as described by Fenneman (1931).

Muleshoe Valley opens into Dry Lake Valley on the south. On the west and north, it is bounded by the southern Schell Creek Range. On the east, it is bounded by Dutch John Mountain, Grassy Mountain, and the Fairview Range (Figure 2). Narrow gaps on the north and east of the valley lead into Lake Valley.

The southern Schell Creek Range is primarily composed of carbonate and siliceous clastic rocks (dolomite, limestone, shale, and quartzite). At the northwest margin of the valley, these sedimentary rocks are overlain by Oligocene welded tuffs and are intruded by minor Tertiary rhyolite dikes and plugs (Ekren and others, 1977). Dutch John Mountain and Grassy Mountain are composed of carbonate and siliceous clastic rocks (limestone, shale, and quartzite) (Tschanz and Pampeyan, 1970); the Fairview Range is composed of middle-Tertiary ash-flow tuff, welded tuff, rhyolite lava, and basalt lava (Ekren and others, 1977). Isolated outcrops of carbonate and siliceous clastic rocks are found in the southern part of the Fairview Range.

The present topographic relief of Muleshoe Valley and the surrounding mountains is largely the result of late-Cenozoic extensional block faulting (Stewart, 1980). Surface data give little indication of the subsurface configuration of the valley.

The Schell Creek Range block on the west appears to be tilted down to the east. Repetition of Oligocene welded tuffs and the underlying Paleozoic rocks in the Dutch John-Grassy-Fairview Range across the valley suggests a major fault along the eastern margin of the valley, but minor faults may also occur beneath the western margin (Ertec, 1981a).

The valley-fill deposits are older alluvium and younger alluvium. The older alluvium is Quaternary in age (Tschanz and Pampeyan, 1970) and consists of nonindurated and partly indurated gravels, sands, and silts derived from the surrounding bedrock (Eakin, 1963). The younger alluvium is composed of reworked older alluvium and is found only in Coyote Wash, the valley's axial drainage channel (Tschanz and Pampeyan, 1970).

Aerial photograph analysis and geologic field reconnaissance (Ertec, 1981a) indicate only a few minor Pleistocene fault scarps breaking the valley-floor surface, although lineaments of unknown origin occur along the southeastern and southwestern valley margins. The Coyote Wash fault extends into Muleshoe Valley from the southwest just north of Silver King Mountain but does not appear to disturb the Quaternary alluvium. Aligned, faceted ridge spurs along the western flank of Dutch John and Grassy mountains suggest Quaternary faulting in the northeastern portion of the valley.

4.0 INTERPRETATION

The basis of interpretation in this report is the Complete Bouguer Anomaly (CBA). Complete Bouguer Anomaly contours and the gravity station locations are shown in Drawing 1.

The interpretation of irregularly spaced data is both difficult and inefficient. In order to simplify the interpretation, the CBA data were reduced to a set of values on the nodes of a regularly spaced grid. The value at each node was computed using a minimum curvature gridding program (Briggs, 1974; and Swain, 1976). Minimum curvature gridding is an iterative process, the purpose of which is to find the smoothest surface that fits the irregularly spaced data. This smooth surface is then used to interpolate between the existing data points. A 0.62-mile (1-km) grid spacing, which is slightly more dense than the average data spacing, was used throughout this analysis.

4.1 REGIONAL RESIDUAL SEPARATION

A fundamental difficulty in gravity interpretation is that the gravity expression of short wavelength, shallow structural features of interest are overlapped and obscured by long wavelength features occurring at all depths. The purpose of a regional-residual separation is to remove the effect of the longer wavelength structures so that the features of interest may be correctly interpreted.

In order to estimate the form and magnitude of the long wavelength contribution (regional), the CBA was continued upward

using a fast Fourier transform (FFT) and a frequency domain filter (Gunn, 1975). The data were continued upward to a height at which no correlation could be seen between the upward-continued CBA and the surface structure. This was at an altitude of 60,000 feet. The regional was then subtracted from the CBA and the resulting residual anomaly was further adjusted by a constant -8.0 mgal to make the zero residual contour approximately fit outcrops of Paleozoic carbonate rocks.

4.2 DENSITY SELECTION

The correct interpretation of the residual anomaly requires density values that are representative of the subsurface rock. In this analysis, only very generalized density information was available. Three borings were drilled approximately 100 feet (30 m) into the alluvium during Verification studies (Ertec, 1981b). The average density measured at the bottom of these borings was slightly less than 2.0 g/cm^3. To account for compaction with depth (Woollard, 1962; and Grant and West, 1965) a density of 2.3 g/cm^3 was assigned to the alluvium.

Basement rocks underlying the alluvium are assumed to be similar to rocks exposed in the nearby mountains. These consist of Tertiary volcanic and plutonic rocks and Paleozoic carbonate and siliceous sedimentary rocks. Published values for the density of the Paleozoic rocks typically range from 2.6 to 2.9 g/cm^3. Carbonate rocks in the Paleozoic section are the most dense with some in Nevada and Utah having values near 2.8 g/cm^3. The siliceous clastic sediments generally have densities ranging

between 2.6 and 2.7 g/cm^3. Densities representative of the Tertiary volcanic rocks range from 2.0 to 2.5 g/cm^3 for tuffaceous material, depending on the degree of welding, compaction, and alteration; from 2.3 to 2.6 g/cm^3 for andesite and rhyolite flows; and from 2.6 to 2.7 g/cm^3 for plutonic rocks.

4.3 MODELING

Modeling was accomplished using three computer programs. Two of these programs compute the gravitational effect of two- and three-dimensional bodies (Talwani and others, 1959; and Plouff, 1975). The third program calculates an inverse three-dimensional solution (Cordell, 1970). The two forward modeling programs were used to augment the inverse modeling program because the inverse program is capable of handling only a single density contrast; whereas, there are several density contrasts that contribute to the form of the residual anomaly.

A contour map showing the thickness of alluvial fill, based on the results of the inverse program, is shown in Drawing 2. The density contrast between alluvium and bedrock used in this analysis was -0.5 g/cm^3. There is very little independent information with which to compare this interpretation. One well, 4N-64E-7dc, drilled to a depth of 1150 feet (351 m) did not penetrate bedrock. Its location is noted in Drawing 2.

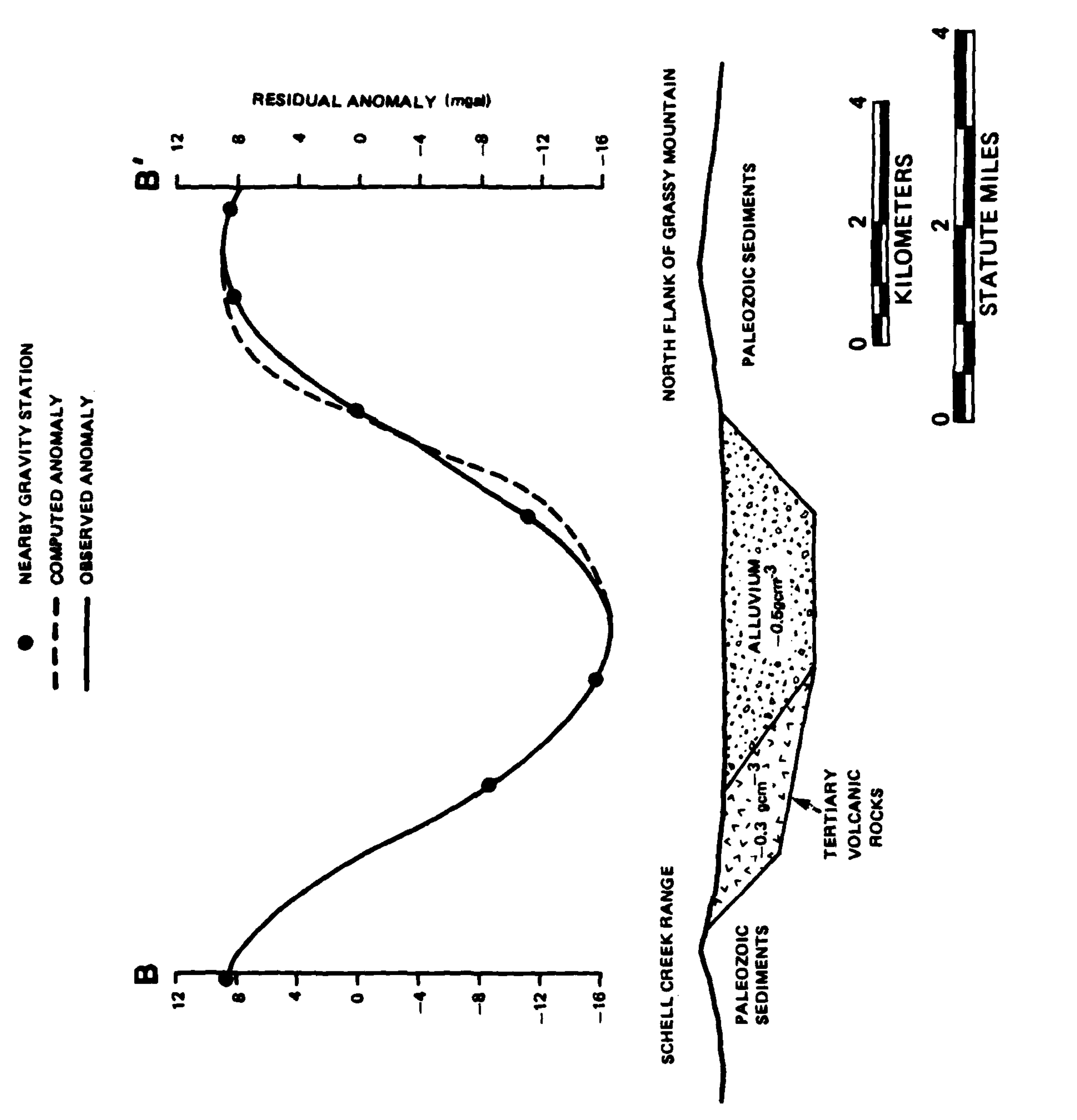
Two gravity profiles were selected for forward modeling with the Talwani program using two density contrasts: -0.5 g/cm^3 for alluvium and -0.3 g/cm^3 for volcanic rock. Profile B-B'

crosses the narrow northern part of the valley and Profile A-A' crosses the deepest part of the valley (Drawing 1). The interpretations resulting from forward modeling are shown in Figures 3A and 3B.

There are three principal sources of error in this analysis. First, because there is no detailed study of the true densities of the rocks, we have had to rely on estimates. Second, the inverse modeling program, upon which most of the interpretation is based, is capable of handling only a single density contrast; whereas, there are probably several density contrasts that contribute to the residual anomaly. Third, the distribution of gravity data in the mountains is not uniform, leaving areas in which the interpretation is based on interpolated trends of the data.

4.4 DISCUSSION OF RESULTS

The interpreted structure of Muleshoe Valley is shown on the contour maps of depth to rock (Drawing 2). Cross-sectional views of the interpreted stratigraphy and structure are shown in Figures 4A and 4B. The interpretations are based on geological information from published reports, analysis of aerial photographs, and geological field reconnaissance as well as gravity data. For example, wherever there was sufficient gravity data, the placement of faults could be made by finding the maximum horizontal gravity gradients. However, in areas lacking detailed gravity data, placement of faults was guided by field reconnaissance and published geologic maps. Major faults on the drawing generally comprise zones of smaller faults.



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CROSS-SECTION B–B'
MULESHOE VALLEY, NEVADA

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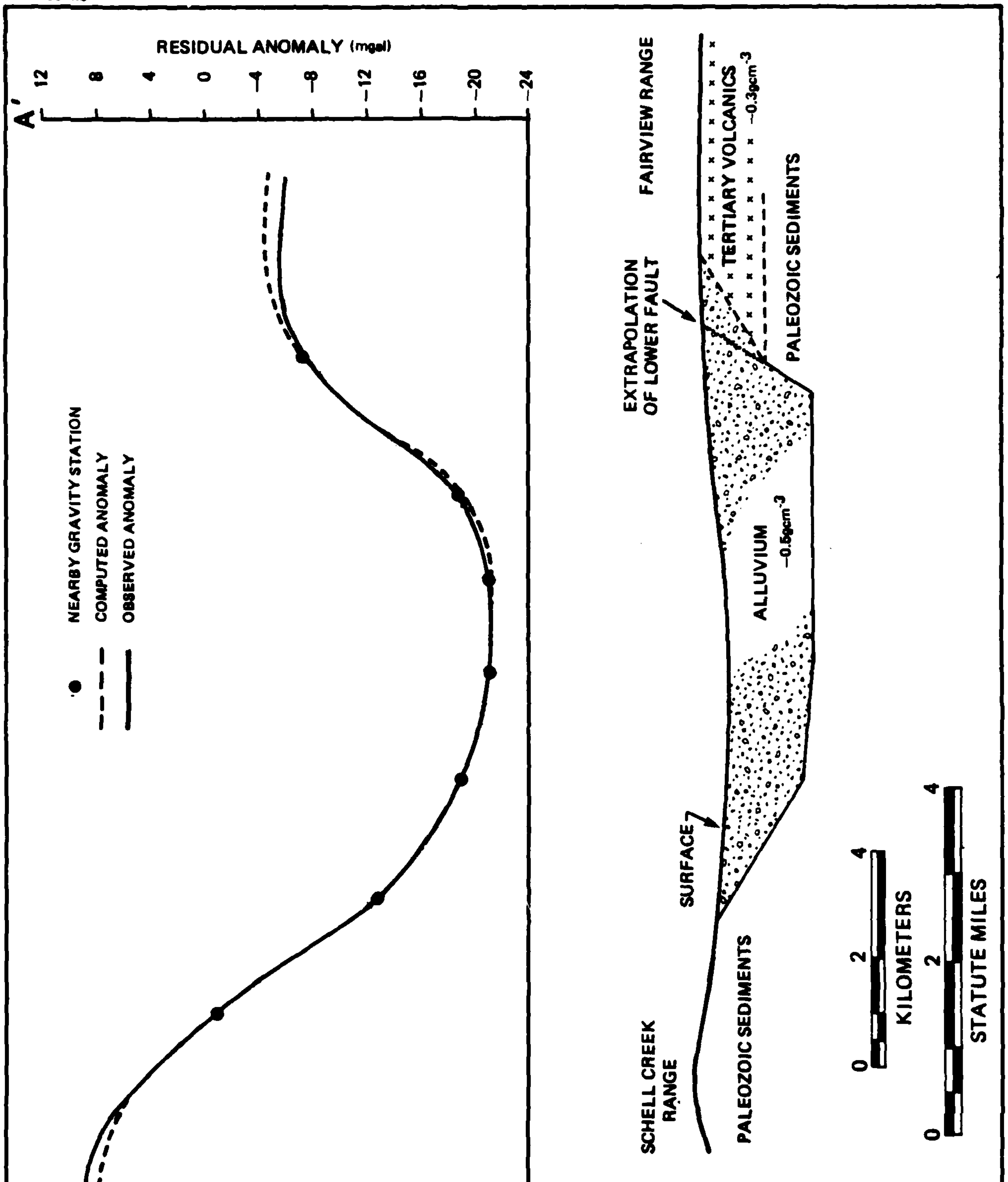
FIGURE 3A



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CROSS-SECTION A–A'
MULESHOE VALLEY, NEVADA

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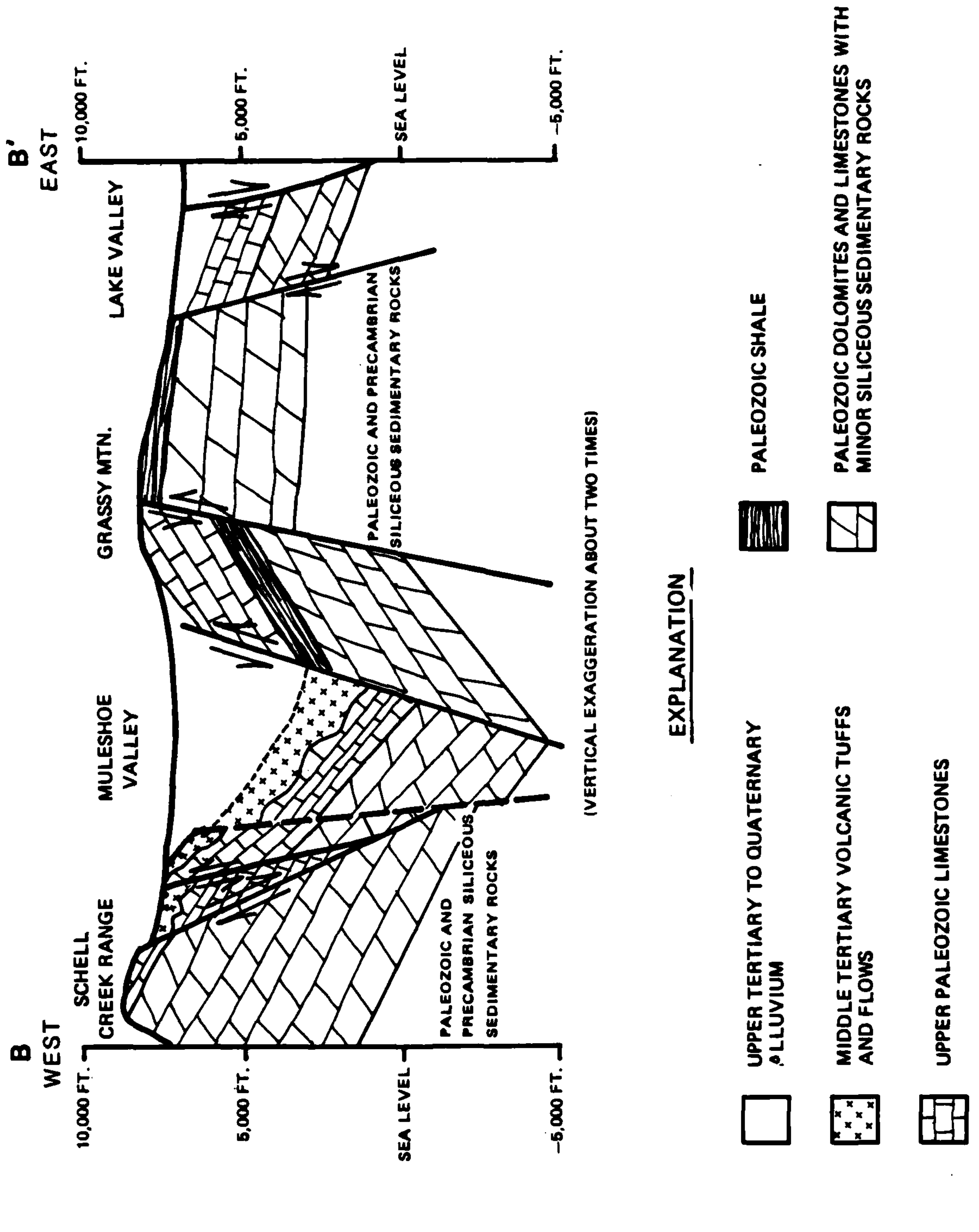
FIGURE 38



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GENERALIZED GEOLOGIC
CROSS-SECTION B–B'
MULESHOE VALLEY, NEVADA

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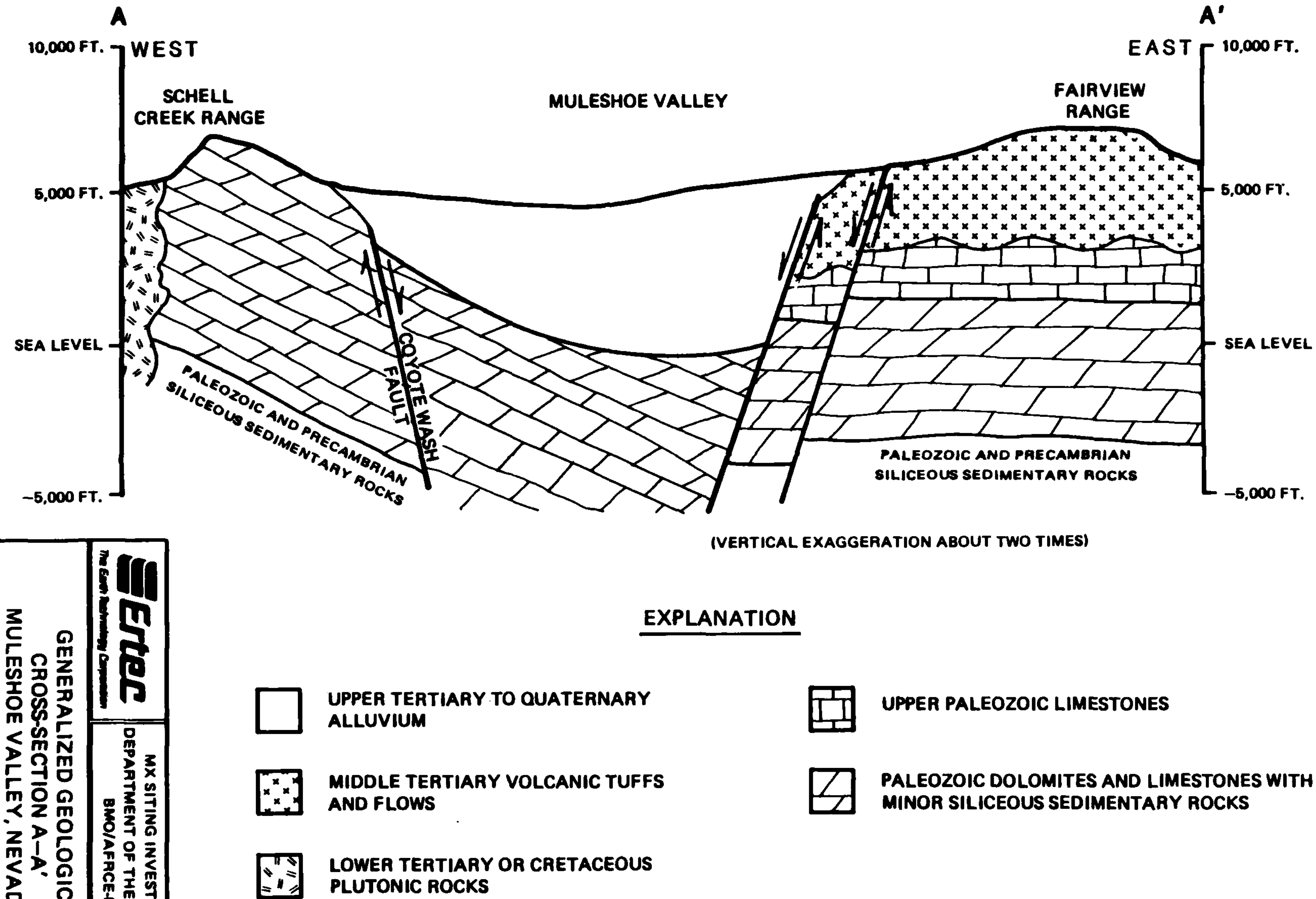

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GENERALIZED GEOLOGIC
CROSS-SECTION A–A'
MULESHOE VALLEY, NEVADA

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In terms of its gravitational expression, Muleshoe Valley is not separated from Lake Valley as much as the topography would suggest. For example, the gravity low crossing the Fairview Range is a consequence of the low density of its volcanic materials. Muleshoe Valley is basically a graben that is wider at its southern end than at its northern end (Drawing 2 and Figure 4). The range-bounding fault on the east side of the valley appears to have more displacement than the corresponding fault on the west side of the valley.

Judging from the results of gravity modeling (Figure 3), the average slope of the base of the alluvium is about 30° on the west side of the valley. On the east side of the valley, the slope is between 45° and 60° in the north, and about 25° in the south. The 25° slope becomes steeper below the volcanic layer (Figure 3B).

The contour map of depth to rock (Drawing 2) shows that there is about 5000 feet (1524 m) of alluvium in the deepest parts of the valley. There may be as much as 3000 feet (914 m) of volcanic rock overlying Paleozoic rock in the Fairview Peak (Figure 2) area. (This estimate is based on a mass defect calculated by planimetric integration of the residual gravity anomaly [described by Grant and West, 1965] and an assumed density contrast of -0.35 g/cm^3 between volcanic rock and Paleozoic rock). It is primarily because of this substantial thickness of volcanic rock that the CBA contours defining Muleshoe Valley cut across the Fairview Range into Lake Valley.

5.0 CONCLUSION

The Complete Bouguer Anomaly data indicate that Muleshoe Valley is an irregular graben that is filled with as much as 5000 feet (1524 m) of alluvium. The deepest part of the graben is generally under the axis of the valley with the maximum depth south of the center. The northern part of the graben is less than half as wide as the southern part. On the west side of the valley, the interface between Paleozoic bedrock and alluvium has a dip of about 30° while the equivalent interface on the east side of the valley has a dip in excess of 50°. This, combined with the observation that the gravity low is displaced eastward with respect to the axis of the valley, indicates that the graben is tilted slightly to the east, as well as to the south. The southern end of the valley has a thin layer of alluvium and volcanic rocks overlying Paleozoic rocks. Apparently the southern end of the graben has no block-like edge but approaches the surface gradually by a stair-step series of unobservably small faults.

5.0 CONCLUSION

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APPENDIX A1.0

GENERAL PRINCIPLES OF THE GRAVITY EXPLORATION METHOD

A1.0 GENERAL PRINCIPLES OF THE GRAVITY EXPLORATION METHOD

A1.1 GENERAL

A gravity survey involves measuring the differences in the gravitational field between various points on the earth's surface. The gravity values are associated with the force which causes a 1 gm mass to be accelerated at 980 cm/sec^2. This force is normally referred to as a 1 g force.

Even though in many applications the gravitational field at the earth's surface is assumed to be constant, small but distinguishable differences in gravity occur from point to point. The differences in gravity are caused by geometrical effects, such as differences in elevation and latitude, and by lateral variations in density within the earth. The lateral density variations are a result of changes in geologic conditions. For measurements at the surface of the earth, the largest factor influencing the pull of gravity is the density of all materials between the center of the earth and the point of measurement.

To detect changes produced by differing geological conditions, it is necessary to detect differences in the gravitational field as small as a few milligals. A milligal is equal to 0.001 cm/sec^2 or 0.00000102 g. To recognize changes due to geological conditions, the measurements are "corrected" to account for changes due to differences in elevation and latitude.

A difference in gravity between two points which is not caused by the effects of known geometrical differences, such as in

elevation, latitude, and surrounding terrain, is referred to as an "anomaly." The anomaly is the basic concept of the gravitational exploration method. If, instead of being an oblate spheroid characterized by complex density variations, the earth were made up of concentric, homogeneous shells, the gravitational field would be the same at all points on the surface of the earth. The complexities in the earth's shape and material distribution are the reason that the pull of gravity is not the same from place to place.

An anomaly reflects lateral differences in material densities. The gravitational attraction is smaller at a place underlain by relatively low density material than it is at a place underlain by a relatively high density material. The term "negative gravity anomaly" describes a situation in which the pull of gravity within a prescribed area is small compared to the area surrounding it. Low-density alluvial deposits in basins such as those in the Nevada-Utah region produce negative gravity anomalies in relation to the gravity values in the surrounding mountains which are formed by more dense rocks.

The objective of gravity exploration is to deduce the variations in geologic conditions that produce the gravity anomalies identified during a gravity survey.

A1.2 INSTRUMENTS

The gravity field data was measured with a LaCoste and Romberg Model D gravimeter. The sensing element of the gravimeter is a mass suspended by a zero-length spring. Deflections of the

mass from a null position are proportional to changes in gravitational attraction. These instruments are sealed and compensated for atmospheric pressure changes. They are maintained at a constant temperature by an internal heater element and thermostat. The absolute value of gravity is not measured directly by a gravimeter. It measures relative values of gravity between one point and the next. Gravitational differences as small as 0.01 milligal can be measured.

A1.3 FIELD PROCEDURES

The gravimeter readings were calibrated in terms of absolute gravity by taking readings twice daily at nearby USGS gravity base stations. Gravimeter readings fluctuate because of small time-related deviations due to the effect of earth tides and instrument drift. Field readings were corrected to account for these deviations. The magnitude of the tidal correction was calculated using an equation suggested by Goguel (1954):

$$C = P + N\cos\phi\,(\cos\phi + \sin\phi) + S\cos\phi\,(\cos\phi - \sin\phi)$$

where C is the tidal correction factor, P, N, and S are time-related variables, and ϕ is the latitude of the observation point. Tables giving the values of P, N, and S are published annually by the European Association of Exploration Geophysicists.

The meter drift correction was based on readings taken at a designated base station at the start and end of each day. Any difference between these two readings after they were corrected for tidal effects was considered to have been the result of

instrumental drift. It was assumed that this drift occurred at a uniform rate between the two readings. Corrections for drift were typically only a few hundredths of a milligal. Readings corrected for tidal effects and instrumental drift represented the observed gravity at each station. The observed gravity values represent the total gravitational pull of the entire earth at the measurement stations.

A1.4 DATA REDUCTION

Several corrections or reductions are made to the observed gravity to isolate the portion of the gravitational pull which is due to the crustal and near-surface materials. The gravity remaining after these reductions is called the "Bouguer Anomaly." Bouguer Anomaly values are the basis for geologic interpretation. To obtain the Bouguer Anomaly, the observed gravity is adjusted to the value it would have had if it had been measured at the geoid, a theoretically defined surface which approximates the surface of mean sea level. The difference between the "adjusted" observed gravity and the gravity at the geoid calculated for a theoretically homogeneous earth is the Bouguer Anomaly.

Four separate reductions, to account for four geometrical effects, are made to the observed gravity at each station to arrive at its Bouguer Anomaly value.

a. Free-Air Effect: Gravitational attraction varies inversely as the square of the distance from the center of the earth. Thus corrections must be applied for elevation. Observed

gravity levels are corrected for elevation using the normal vertical gradient of:

$$FA = -0.09406 \text{ mg/ft } (-0.3086 \text{ milligals/meter})$$

where FA is the free-air effect (the rate of change of gravity with distance from the center of the earth). The free-air correction is positive in sign since the correction is opposite the effect.

b. <u>Bouguer Effect</u>: Like the free-air effect, the Bouguer effect is a function of the elevation of the station, but it considers the influence of a slab of earth materials between the observation point on the surface of the earth and the corresponding point on the geoid (sea level). Normal practice, which is to assume that the density of the slab is 2.67 grams per cubic centimeter was followed in these studies. The Bouguer correction (B_c), which is opposite in sign to the free-air correction, was defined according to the following formula.

$$B_c = 0.01276\ (2.67)\ h_f \text{ (milligals per foot)}$$

$$B_c = 0.04185\ (2.67)\ h_m \text{ (milligals per meter)}$$

where h_f is the height above sea level in feet and h_m is the height in meters.

c. <u>Latitude Effect</u>: Points at different latitudes will have different "gravities" for two reasons. The earth (and the geoid) is spheroidal, or flattened at the poles. Since points at higher latitudes are closer to the center of the earth than points near the equator, the gravity at the higher latitudes is larger. As the earth spins, the centrifugal acceleration

causes a slight decrease in gravity. At the higher latitudes where the earth's radii are smaller, the centrifugal acceleration diminishes. The gravity formula for the Geodetic Reference System, 1967, gives the theoretical value of gravity at the geoid as a function of latitude. It is:

$$g = 978.0381\ (1 + 0.0053204\ \sin^2 \phi - 0.0000058\ \sin^2 2\phi)\ \text{gals}$$

where g is the theoretical acceleration of gravity and ϕ is the latitude in degrees. The positive term accounts for the spheroidal shape of the earth. The negative term adjusts for the centrifugal acceleration.

The previous two corrections (free air and Bouguer) have adjusted the observed gravity to the value it would have had at the geoid (sea level). The theoretical value at the geoid for the latitude of the station is then subtracted from the adjusted observed gravity. The remainder is called the Simple Bouguer Anomaly (SBA). Most of this gravity represents the effect of material beneath the station, but part of it may be due to irregularities in terrain (upper part of the Bouguer slab) away from the station.

d. Terrain Effect: Topographic relief around the station has a negative effect on the gravitational force at the station. A nearby hill has upward gravitational pull and a nearby valley contributes less downward attraction than a nearby material would have. Therefore, the corrections are always positive. Corrections are made to the SBA when the terrain effects were 0.1 milligal or larger. Terrain corrected Bouguer values are

called the Complete Bouguer Anomaly (CBA). When the CBA is obtained, the reduction of gravity at individual measurement points (stations) is complete.

A1.5 INTERPRETATION

To interpret the gravity data, the portion of the CBA that might be caused by the light-weight, basin-fill material must be separated from tha. caused by the heavier bedrock material which forms the surrounding mountains and presumably the basin floor. The first step is to create a regional field. A regional field is an estimation of the values the CBA would have had if the light-weight sediments (the anomaly) had not been there. Since the valley-fill sediments are absent at the stations read in the mountains, one approach is to use the CBA values at bedrock stations as the basis for constructing a second order polynomial surface to represent a regional field over the valley.

Where there are insufficient bedrock stations to define a satisfactory regional trend, another approach is to estimate the regional by the process of upward continuation of the CBA field.

In Potential Theory, a field normal to a surface, regardless of its actual source, may be considered as originating in an areal distribution of mass on that surface. If the field strength is known the surface density of mass (grams per square centimeter) can be calculated. The observed gravity field at the surface of the earth approximately fulfills the requirements of this theory: thus the observed (Bouguer anomaly) field can be used

to compute a surficial distribution of mass which would reproduce the field, and most importantly, account for the gravity field anywhere above the surface of observation. On this basis, the Bouguer anomaly field is readily "continued" to level surfaces above the ground.

An important property of such "upward continuation" is that the resultant field with increasing altitudes of continuation, changes more with respect to shallow sources than it does with respect to deeper sources. The anomalous parts of the field ascribed to shallow density distribution tend to vanish as the continuation is carried upward whereas the field produced by deeper sources changes only slightly, so that upward continuations produce "regional"-type fields.

The difference between the CBA and the regional field is called the "residual" field or residual anomaly. The residual field is the interpreter's estimation of the gravitational effect of the geologic anomaly. The zero value of the residual anomaly is not exactly at the rock outcrop line but at some distance on the "rock" side of the contact. The reason for this is found in the explanation of the terrain effect. There is a component of gravitational attraction from material which is not directly beneath a point.

If the "regional" is well chosen, the magnitude of the residual anomaly is a function of the thickness of the anomalous (fill) material and the density contrast. The density contrast is the difference in density between the alluv[illegible] and bedrock material.

If this contrast were known, an accurate calculation of the thickness could be made. In most cases, the densities are not well known and they also vary within the study area. In these cases, it is necessary to use typical densities for materials similar to those in the study area.

If the selected average density contrast is smaller than the actual density contrast, the computed depth to bedrock will be greater than the actual depth and vice-versa. The computed depth is inversely proportional to the density contrast. A ten percent error in density contrast produces a ten percent error in computed depth. An iterative computer program is used to calculate a subsurface model which will yield a gravitational field to match (approximately) the residual gravity anomaly.

The second vertical derivative (SVD) of gravitational field is used to aid the interpreter in evaluating the subsurface mass distribution. Once the CBA field has been projected onto a uniform grid system, its SVD at the grid nodes is readily computed. In accordance with LaPlace's Equation in Free Space, the negative of the second vertical derivative is equal to the sums of the second derivatives in the x-direction and in the y-direction. The second vertical derivative is an indication of the curvature of the Bouguer anomaly field. In particular the zero-value of the SVD indicates the inflection in the field as it changes from "concave-upward" (algebraically negative SVD) to "convex-upward" (algebraically positive SVD). In a general way the zero SVD falls on the tightest contours of the field and

where contours are nearly parallel its location can be established by eye. However, where contours diverge, converge, or change direction this is not always so readily done. The zero SVD contour line may be an indicator of a line of faulting, the pinchout of a stratum, truncation of a stratum at an unconformity or merely a marked change in shape or in density of a geologic unit.

APPENDIX A2.0

MULESHOE VALLEY, NEVADA

GRAVITY DATA

MULESHOE VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG	MIN	LONG. DEG MIN ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM	EAST UTM OBSV GRAV THEO GRAV	FAA	CBA +1000
0260	38	515	1143875616 90T	0	216421775	70647143554199963	1610	80796
0262	38	520	114407455889T	0	138421777	70356146709199970	-680	80388
0263	38	531	114414254629T	0	132421795	70256147609199986	-990	80512
0282	38	564	114427452881T	0	136421851	70061149557200035	-730	81366
0266	38	575	114392958560T	0	187421884	70565145175200051	200	80427
0275	38	593	114402556280T	0	145421914	70424146313200077	-820	80125
0278	38	602	114417554062T	0	128421925	70204147913200090	-1320	80368
5029	38	622	114413254511T	0	137421963	70266147426200120	-1410	80137
0294	38	623	114449152500T	0	121421952	69741149611200121	-1120	81091
0274	38	627	114406255600T	0	135421975	70368146706200127	-1120	80055
1914	38	640	114489250951T	0	92421970	69155149925200146	-2290	80422
0157	38	658	114478351161T	0	96422007	69313149692200172	-2350	80296
0273	38	664	114399056660T	0	149422046	70472145711200181	-1170	79659
0154	38	675	114467551801T	0	101422042	69470149198200197	-2270	80161
0297	38	687	114423755000T	0	122422080	70110147246200215	-1230	80132
0158	38	692	114456152530T	0	107422078	69636149307200222	-1500	80687
0295	38	705	114443353930T	0	123422106	69822148584200241	-920	80803
0296	38	710	114432055230T	0	129422119	69987147473200248	-820	80469
7412	38	710	114441153930T	0	127422116	69854148611200248	-900	80837
0276	38	711	114412156220T	0	121422128	70278146571200250	-790	80151
0156	38	721	114476051709T	0	105422124	69344149708200265	-1910	80555
0271	38	730	114391858281T	0	149422171	70574145057200278	-390	79879
0270	38	740	114382459911T	0	183422193	70711144838200292	900	80653
7411	38	750	114380061529T	0	150422212	70745143580200307	1140	80320
0008	38	751	114450555479T	0	113422189	69715147515200308	-600	80593
0781	38	761	114430357749T	0	126422214	70010146652200323	650	81086
0780	38	762	114438556181T	0	107422213	69890146994200325	-480	80467
0782	38	771	114422556270T	0	124422236	70123146360200333	-1040	79884
0790	38	794	114396857621T	0	145422288	70498145868200371	-300	80195
0784	38	807	114442158560T	0	147422295	69835145467200390	160	80337
0005	38	808	114485256339T	0	197422282	69206147010200392	-380	80597
0783	38	815	114427456870T	0	126422315	70050146386200402	-520	80216
0785	38	819	114449157021T	0	122422315	69733146525200408	-240	80432
0004	38	833	114499751509T	0	119422323	68993149882200428	-2090	80459
0793	38	834	114387858471T	0	202422365	70627146123200430	690	80952
0009	38	861	114455056650T	0	115422391	69645146898200469	-280	80515
0786	38	873	114435257470T	0	122422420	69933146343200487	-80	80442
0010	38	880	114467256001T	0	112422421	69465147321200497	-500	80512
0800	38	892	114427660341T	0	149422458	70043144701200515	940	80519
0011	38	892	114477355840T	0	111422440	69317147348200515	-640	80431
0012	38	899	114489852510T	0	105422449	69135149678200525	-1450	80745

MULESHOE VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG MIN	LONG. DEG MIN ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM EAST UTM OBSV GRAV THEO GRAV	FAA	CBA +1000
0013	38 914	114499951860T	0	132422473 6898614991 1200547	-1850	80592
0787	38 922	114444556850T	0	135422507 69795146689200559	-390	80355
0018	38 939	114493455850T	0	152422521 69080147262200584	-780	80322
0020	38 944	114466958261T	0	131422540 69467145919200591	120	80391
0021	38 946	114455859341T	0	175422547 69629145187200594	410	80355
0811	38 957	114379361329T	0	123422596 70746144341200610	1410	80633
0804	38 963	114432361171T	0	163422587 69971144694200619	1610	80923
0019	38 966	114483754692T	0	94422575 69221148305200623	-870	80574
0022	38 991	114457258471T	0	119422630 69607145899200660	230	80419
0803	38 997	114440060732T	0	150422647 69857144782200669	1230	80680
0026	381003	114498252251T	0	128422638 69007149740200677	-1780	80518
7286	381005	114362160246T	0	117422691 70995143831200680	-170	79397
0805	381005	114426366581T	0	386422667 70057141111200680	3050	80736
0024	381013	114475254491T	0	128422665 69343148398200692	-1030	80508
0023	381024	114465856280T	0	97422688 69480147015200708	-750	80147
0025	381034	114487656319T	0	111422699 69161146865200723	-880	80021
7442	381055	114436860397T	0	140422756 69902145498200754	1550	81110
0819	381068	114442559531T	0	125422778 69818145722200773	940	80775
0032	381074	114476256969T	0	114422777 69325146449200781	-740	79944
0034	381079	114457057110T	0	103422793 69606147198200789	120	80763
0033	381084	114467255341T	0	100422799 69456147848200796	-890	80340
0031	381090	114495752710T	0	126422800 69040149004200805	-2210	79936
0820	381149	114443961680T	0	161422927 69794143784200891	910	80041
1582	381230	114353060961T	0	122423110 71117143702201010	30	79382
7440	381410	114483853960T	0	132423396 69200147951201274	-2560	79172
1210	381418	114353061821T	0	115423458 71108143516201285	380	79425
7049	381430	114355061837T	0	119423480 71078143601201303	460	79499
7441	381515	114422060843T	0	121423612 70097144428201427	220	79611
1581	381530	114354062359T	0	114423665 71088143242201449	440	79314
1580	381730	114359062139T	0	132424033 71005143802201742	500	79462
7443	381775	114496062487T	0	191424067 69006145059201808	2020	80921
7424	381825	114419059551T	0	195424186 70126145228201882	-630	79255
7032	381916	114363061568T	0	141424375 70938144291202015	180	79341
1209	381932	114364261624T	0	140424405 70920144257202039	180	79320
7423	382020	114433557799T	0	273424542 69906146055202168	-1730	78823
1579	382060	114369060679T	0	127424640 70844144962202226	-190	79247
7031	382304	114373859760T	0	125425089 70762146083202584	-280	79455
1578	382330	114381060259T	0	145425227 70654146302202696	280	79885
7283	382535	114433862221T	0	169425494 69878144719202923	320	79289
7419	382545	114486560312T	0	135425494 69111147334202938	1120	80705
7220	382550	114486560285T	0	134425503 69110147335202945	1090	80684

MULESHOE VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG MIN	LONG. DEG MIN ELEV. +CODE	TER-COR. IN/OUT NORTH UTM	EAST UTM OBSV GRAV THEO GRAV	FAA	CBA +1000
1208	382590	114382259892T	0 230425615	70626146525203004	-140	79670
1577	382720	114386059419T	0 330425854	70565147072203195	-230	79840
7030	382782	114386259846T	0 204425969	70559146772203286	-210	79574
1589	382900	114387060141T	0 134426187	70542146652203459	-230	79394
LV0124	382875	1143571 5915Y	0 97426152	70978144475203422	-3278	76645
LV0162	382686	1144012 8860V	463635425785	70345127201203145	7461	80923
LV0164	382468	1143811 5998C	0 180425390	70648146494202825	120	79843
LV0173	381791	1143794 7866V	561888424138	70705132802201832	5013	80128
LV0201	381690	1143564 6227Y	0 123423960	71045143519201684	443	79328
LV0163	382590	1143815 6007C	0 408425615	70636146418203004	-49	79871
LV0262	381250	1143635 6538Y	7 260423143	70963141118201039	1615	79583
CAV073	382274	1144861 7406C	322236424993	69128137344202540	4514	81522
CAV075	382399	114487560420T	0 241425224	69102147125202724	1267	80901
CAV086	382676	1144560 7383V	38 951425747	69549137667203130	4030	79838
CAV093	382030	1144947 8114C	673245424539	69014131891202182	6086	81724
CAV085	382461	1144769 7048C	94 573425342	69254139556202814	3080	79708
LV0156	382896	1144382 7574C	16 591426160	69797137075203453	4914	79688
LV0165	382428	1144070 7048C	6 347425306	70273141407202766	4979	81293
LV0170	382090	1144031 8613C	122214424682	70345128958202270	7766	80615
LV0282	38 539	1143645 7907V	261624421828	70982131683199998	6114	80795
CAV070	382764	1144992 6010S	0 114425895	68916145314203259	-1381	78234
CAV074	382317	114491760321T	0 176425071	69045146861202603	1030	80632
CAV076	382482	1144933 5981S	0 117425375	69014145982202845	-573	79145
CAV077	382572	1144950 5990S	0 109425541	68986145549202977	-1053	78626
CAV078	382668	1144947 6001C	0 111425719	68986145434203118	-1205	78438
CAV079	382789	1144886 6018S	0 121425945	69069145451203296	-1205	78390
CAV080	382895	1144903 6030S	0 127426140	69040145273203451	-1426	78134
CAV081	382983	1144868 6043S	0 138426304	69087145588203581	-1118	78409
CAV082	382885	114476260420T	0 154426127	69245146084203437	-487	79059
CAV083	382678	1144803 6022C	0 142425742	69195147048203133	592	80195
CAV084	382547	114484460312T	0 157425499	69141147321202941	1142	80729
CAV087	382764	1144642 6321C	0 218425907	69425145771203259	2004	80663
CAV088	382856	1144620 6401B	0 248426096	69453145279203409	2116	80532
CAV091	382196	114485061089T	0 225424849	69148146657202426	1728	81117
CAV092	382164	114495960200T	0 345424786	68990147056202379	1336	81148
LV0123	382970	1143694 5921Y	0 103426323	70794144749203562	-3087	76821
LV0129	382727	1143677 5919Y	0 114425874	70831145236203205	-2261	77665
LV0136	382618	1143631 5921Y	0 109425674	70903145414203045	-1905	78010
LV0137	382501	1143597 5927Y	0 104425459	70958145454202873	-1636	78252
LV0144	382421	1143575 5929Y	0 103425312	70994145313202756	-1641	78240
LV0146	382324	1143584 5936Y	0 104425132	70985145389202613	-1357	78501

MULESHOE VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG MIN	LONG. DEG MIN	ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM	EAST UTM	OBSV GRAV	THEO GRAV	FAA	CBA +1000
LV0153	382979	1143884	5998B	0	122426332	70518146686203575			-438	79227
LV0154	382927	1144004	6097C	0	153426231	70346146165203499			50	79408
LV0155	382930	1144103	6220C	0	164426233	70202145257203503			296	79245
LV0157	382794	1144171	6316C	0	212425979	70109144777203303			919	79589
LV0158	382846	1144046	6246B	0	209426080	70288145570203380			977	79883
LV0159	382855	1143932	6056C	0	185426101	70454146520203393			124	79654
LV0160	382849	1143766	5937Y	0	120426096	70695145896203384			-1611	78259
LV0161	382734	1143843	5938C	0	240425880	70589146831203215			-498	79489
LV0166	382377	1143898	6146C	0	183425218	70526146614202691			1768	80989
LV0167	382326	1144027	6445Y	0	206425119	70340144953202616			2997	81221
LV0168	382278	1143787	6048C	0	138425039	70692145970202546			346	79856
LV0169	382172	1143877	6375B	0	235424840	70566144535202391			2145	80637
LV0171	382041	1143836	6407B	0	218424599	70632143833202198			1937	80302
LV0172	381951	114377162441T		0	171424435	70731144516202066			1218	80092
LV0174	382240	114364859550T		0	111424974	70896145699202490			-744	79056
LV0175	382240	114354159531T		0	100424978	71052145135202490			-1327	78469
LV0180	382129	1143541	5960Y	0	103424773	71057145148202327			-1086	78689
LV0181	382131	1143697	6023Y	0	126424771	70830145488202330			-156	79427
LV0182	382046	1143676	6075Y	0	122424614	70865144673202206			-355	79046
LV0188	381999	1143526	5997S	0	105424533	71085144303202137			-1392	78259
LV0189	381910	114363761621T		0	142424364	70928144232202006			221	79346
LV0202	381574	114355762359T		0	116423746	71061143241201514			420	79266
LV0254	381460	1143550	6190S	0	117423535	71076143556201347			468	79473
LV0296	382327	1143716	5957Y	0	120425132	70793146043202618			-510	79293
MSV076	381303	1144439	5847V	23	114423212	69787145469201117			-618	79577
MSV075	381149	1144439	6168S	201	159422927	69794143805200891			966	80289
CAV086	382676	1144560	7383C	238	634425747	69549137676203130			4040	79730
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MSV021	381935	1144165	7396S	609	874424391	70157136904202043			4477	80734
MSV015	381801	1143942	7418S	22	820424151	70489136569201847			4546	80087
MSV016	381545	1143959	6877C	16	254423677	70476139408201471			2665	79480
MSV052	381849	1144961	7190C	27	787424204	69001138329201917			4088	80379
MSV080	381213	1144109	7239S	22	698423057	70272136185200985			3337	79367
CAV085	382461	1144769	7048C	0	576425342	69254139553202814			3077	79614
CAV091	382196	114485061089T		0	219424849	69148146653202426			1724	81107
MSV001	382271	1144651	6039V	0	114424995	69434145796202536			97	79614
MSV002	382330	1144664	6150C	0	131425196	69410145525202696			712	79867
MSV003	382423	1144540	6202C	0	125425280	69589144875202759			488	79460

MULESHOE VALLEY GRAVITY DATA

```
STATION  LAT.    LONG.  ELEV.  TER-COR.  NORTH EAST   OBSV    THEO   FAA    CBA
IDENT.  DEG MIN DEG MIN +CODE   IN/OUT    UTM    UTM  GRAV    GRAV          +1000

MSV004 382295 1144515 6002C    0 114425044 69631145270202571  -812 78831
MSV005 382308 1144390 6088S    0 136425073 69813145024202590  -267 79104
MSV006 382441 1144379 6134S    0 145425319 69823144979202785   -74 79149
MSV007 382538 1144346 6230S    0 167425500 69866144692202928   401 79319
MSV008 382655 1144272 6396S    0 203425719 69968144182203099  1282 79670
MSV009 382725 1144209 6445S    0 220425850 70057144036203202  1494 79732
MSV011 382416 1144273 6338S    0 171425277 69978144376202748  1281 79835
MSV012 382285 1144276 6356C    0 179425034 69980144494202556  1760 80260
MSV017 381547 1144098 6255S    0 139423676 70273143308201474   706 79510
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MSV022 382182 1144269 6390V    0 211424844 69995144371202405  2108 80524
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MSV046 381951 1144691 5982C    0 143424402 69390145419202066  -347 79393
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MSV048 381757 1144836 5892C    0 139424038 69187145413201782  -916 79127
MSV049 381650 1144876 5782C    0 125423838 69134145983201625 -1224 79180
MSV050 381514 1144919 5595C    0 119423585 69077146995201426 -1774 79262
```

MULESHOE VALLEY GRAVITY DATA

STATION IDENT.	LAT. DEG MIN	LONG. DEG MIN	ELEV. +CODE	TER-COR. IN/OUT	NORTH UTM	EAST UTM	OBSV GRAV	THEO GRAV	FAA	CBA +1000
MSV051	381765	1144951	6110C	0 174	424049	69019	145440	201794	1152	80487
MSV061	381407	1144956	5552Y	0 115	423386	69028	147159	201269	-1858	79321
MSV062	381435	1144818	5468Y	0 118	423443	69228	147432	201310	-2416	79052
MSV063	381338	1144874	53970T	0 128	423261	69150	147931	201168	-2444	79276
MSV064	381252	1144904	53599T	0 118	423101	69110	148495	201042	-2103	79734
MSV065	381169	1144930	53271T	0 122	422947	69076	148650	200920	-2137	79816
MSV066	381039	1144957	52710T	0 124	422798	69040	149016	200803	-2181	79965
MSV067	381074	1144762	5697Y	0 113	422777	69325	146467	200781	-697	79985
MSV068	381203	1144760	5453V	0 104	423016	69323	148344	200970	-1306	80199
MSV069	381334	1144723	5516V	0 99	423259	69371	147241	201162	-2007	79278
MSV070	381479	1144622	5649V	0 97	423531	69512	146112	201375	-2096	78734
MSV071	381330	1144559	5692V	0 100	423350	69608	146031	201230	-1628	79058
MSV072	381247	1144589	5632V	0 108	423103	69570	146596	201035	-1433	79466
MSV073	381160	1144654	5539V	0 104	422940	69479	147758	200907	-1020	80192
MSV074	381080	1144570	5711Y	0 105	422795	69606	147218	200790	177	80803
MSV077	381490	1144467	5806Y	0 102	423557	69737	145184	201391	-1563	78736
MSV078	381376	1144347	6005Y	0 116	423350	69918	143795	201224	-911	78723
MSV079	381460	1144208	6107S	0 131	423511	70117	144240	201347	372	79674
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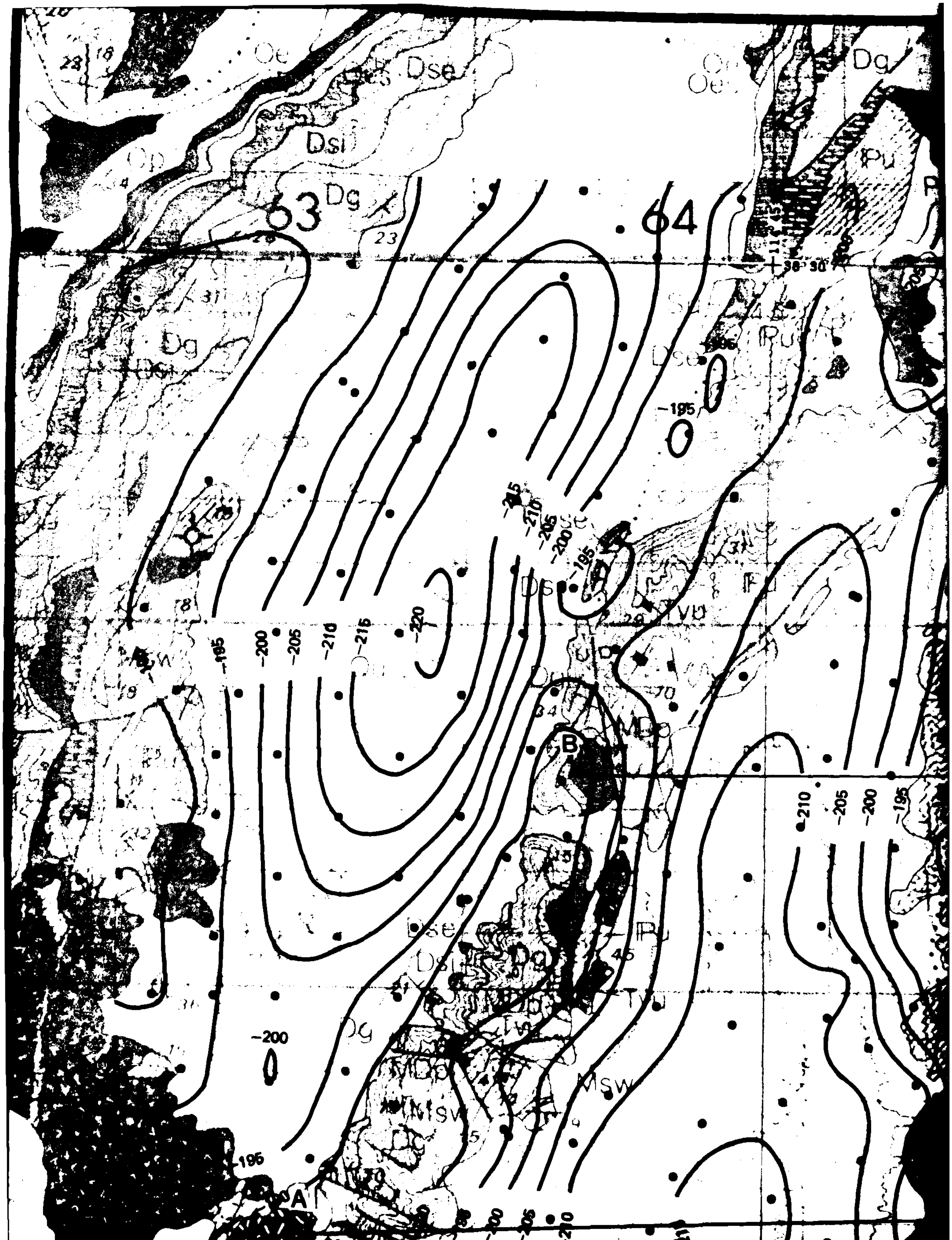
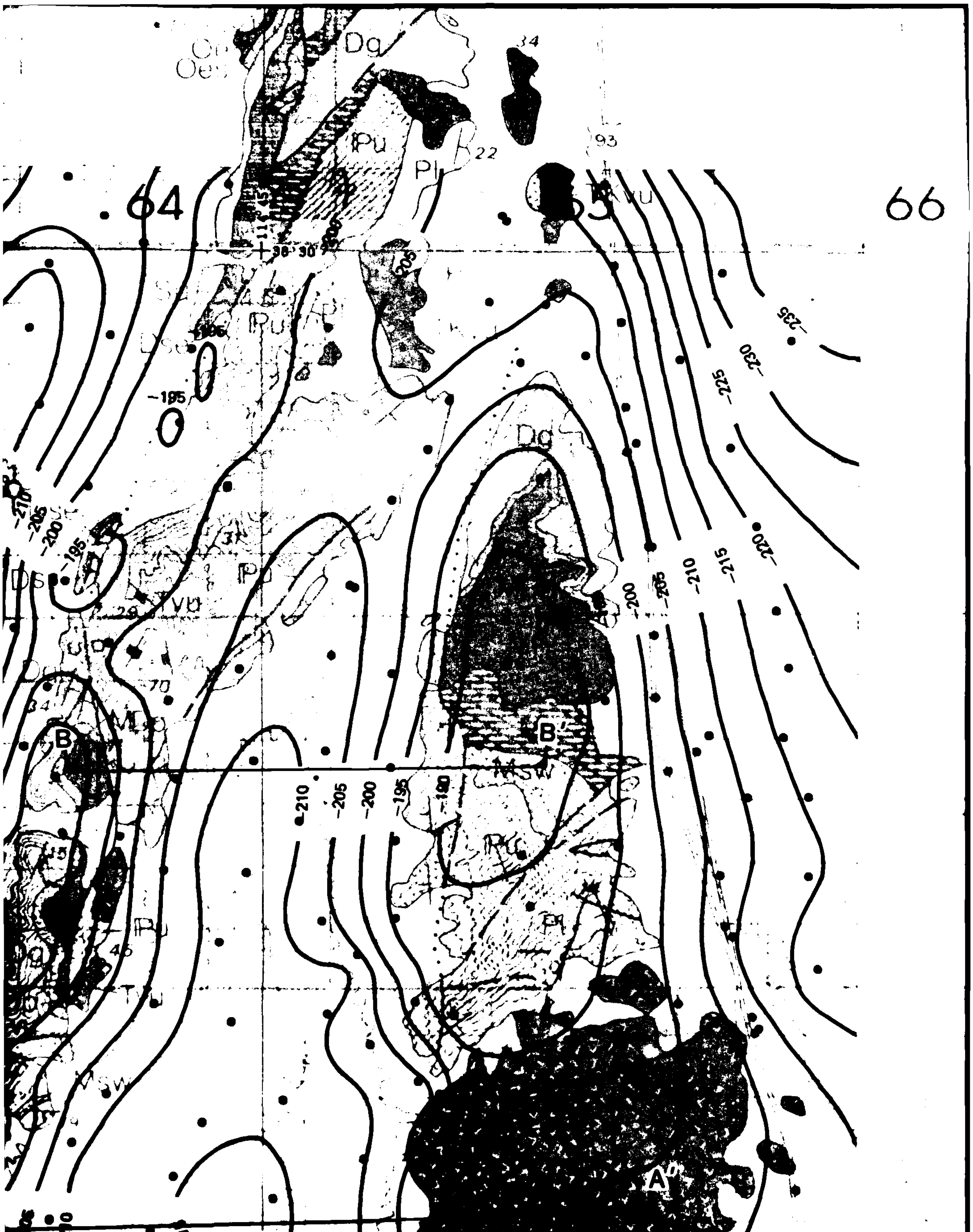
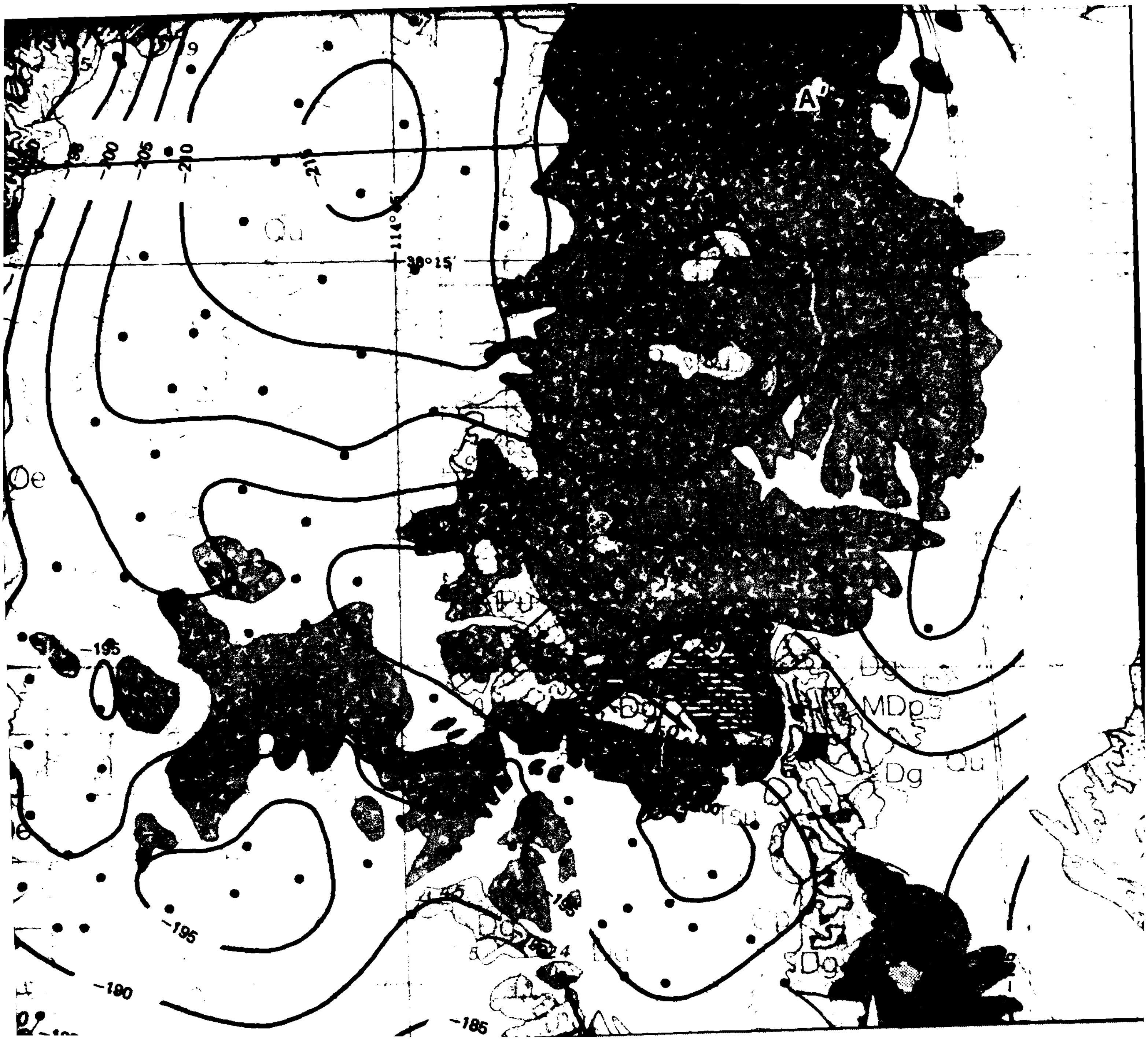


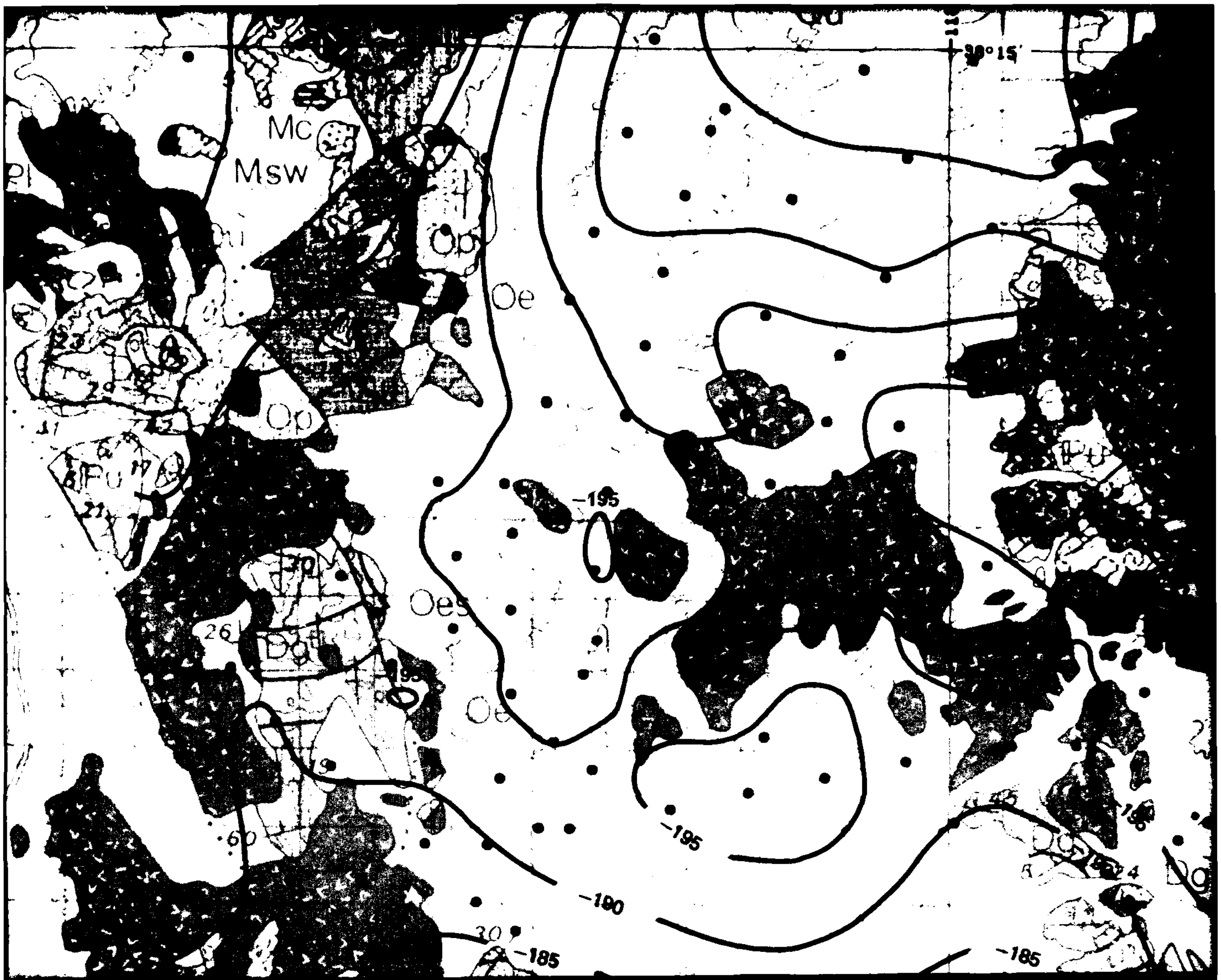
63
64
Dse
Dsi
Dg
Oe
Pu
-195
-200
-205
-210
-215
-220
B
A
Msw
MDp


64
66
Dg
Pu
Pl
B
B'
A''
Msw
-190
-195
-200
-205
-210
-215
-220
-225
-230
-235

Msw
Msw
Mc
Op
Op
Oe
-195
-190
-185
-185
-195
-200
-205
-210
-215
38°15'
111°



Qu
Oe
Dg
MDp
SDg
-195
-190
-185
-200
-205
-210
A'



EXPLANATION

FAULTS SHOWN ON GEOLOGIC BASE MAP:

NORMAL

INFERRED

CONCEALED

ALLUVIAL MATERIAL

ROCK (ALL PATTERNS)

GRAVITY STATIONS

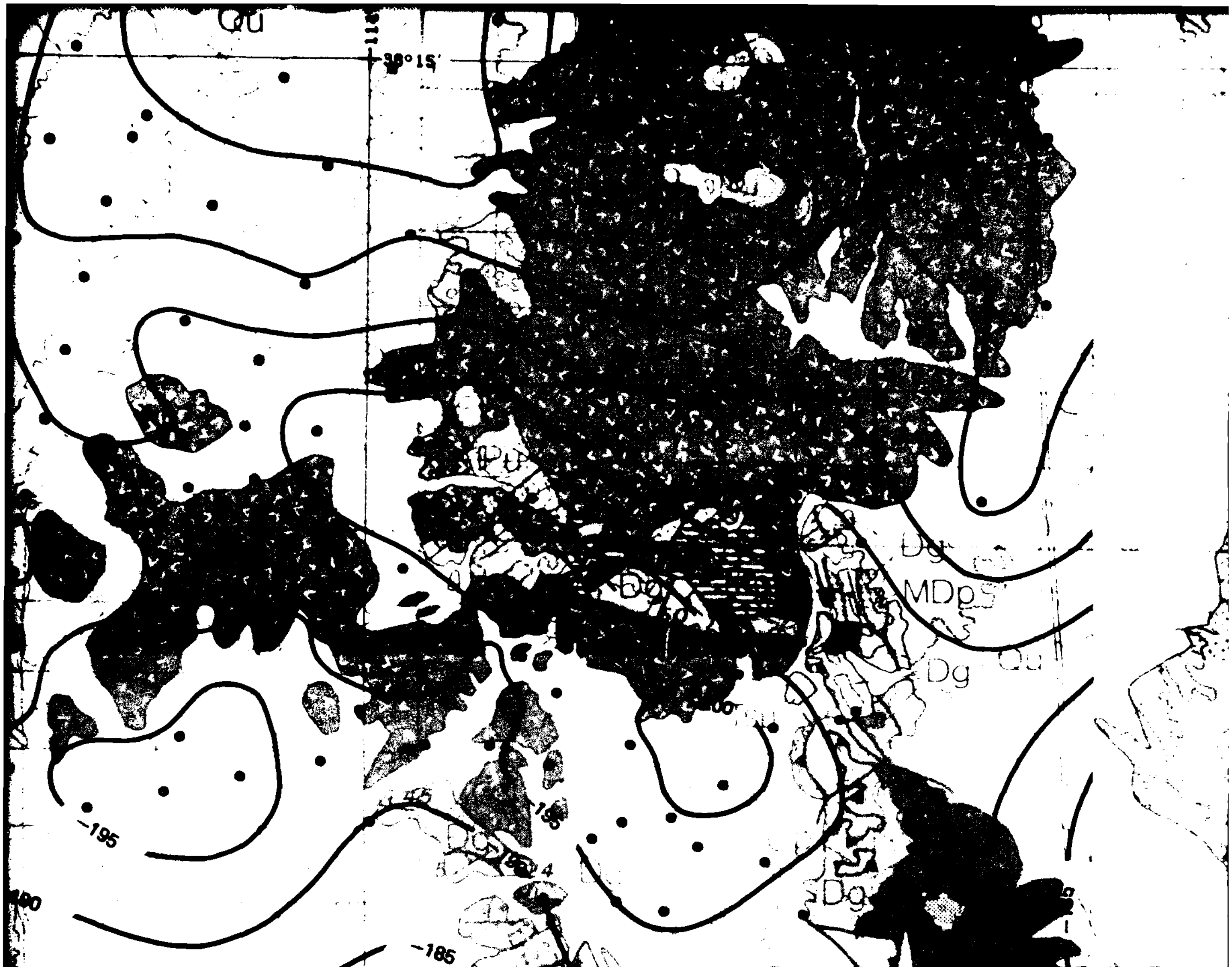
NORTH

A A'

LOCATION OF PROFILE

CONTOUR INTERVAL = 5 MILLIGALS

GEOLOGIC BASE MAP: E.L.Howard (19



MAP:

NORTH

SCALE 1: 125,000

0 2 4
STATUTE MILES

0 2 4
KILOMETERS

A A'

LOCATION OF PROFILE

CONTOUR INTERVAL = 5 MILLIGALS

GEOLOGIC BASE MAP: E.L.Howard (1978)

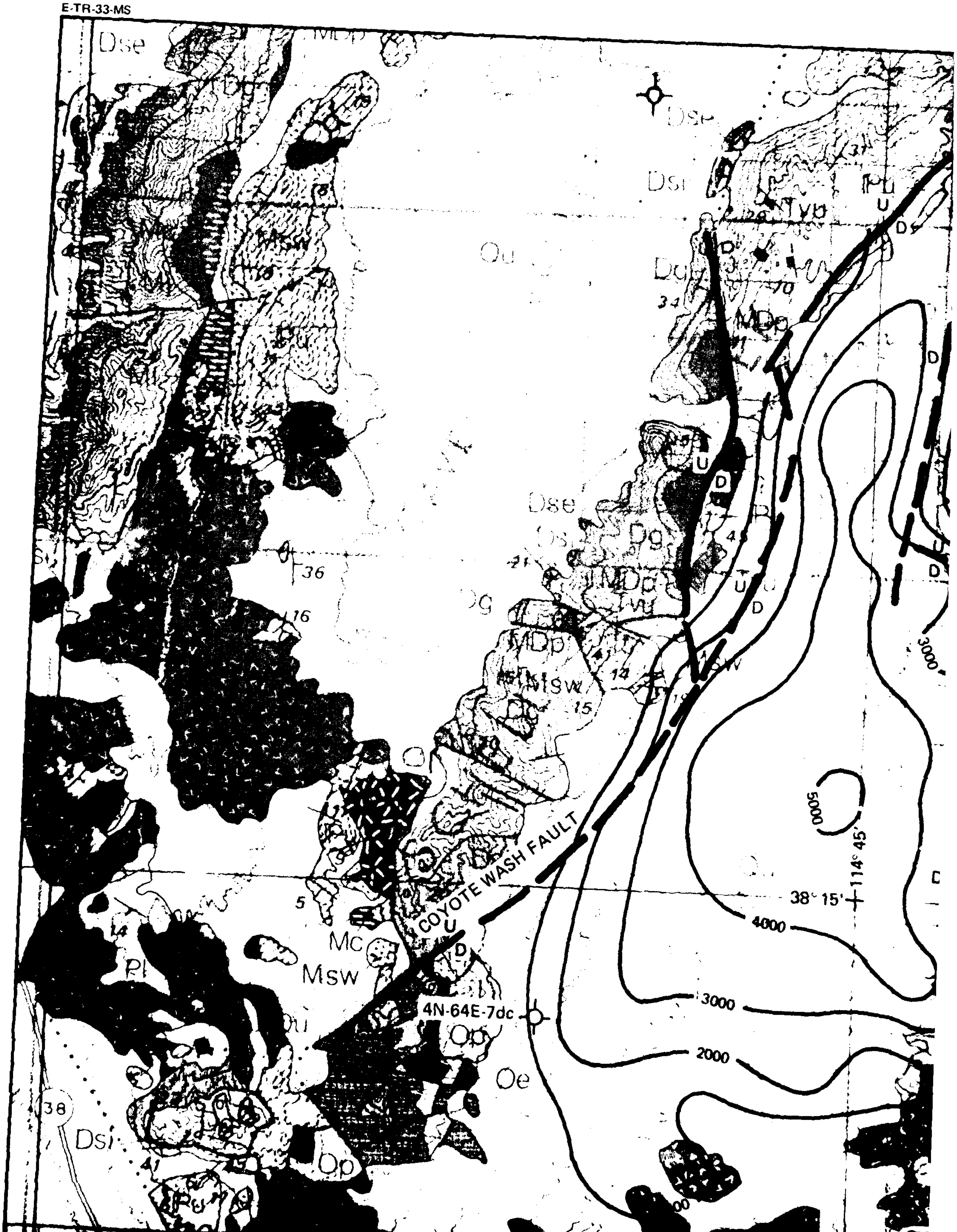
Ertec
The Earth Technology Corporation

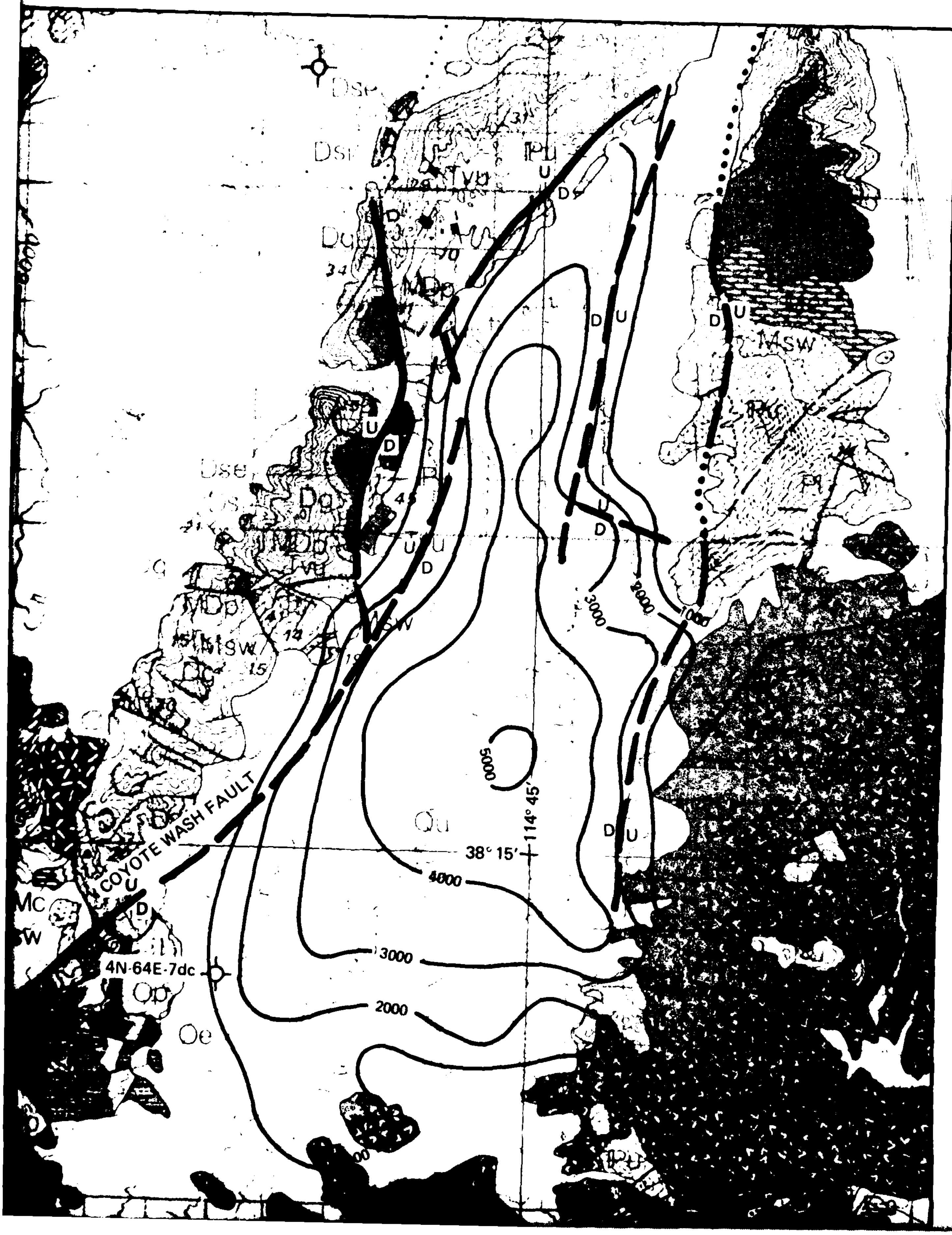
MX SITING INVESTIGATION
DEPARTMENT OF THE AIR FORCE
BMO/AFRCE-MX

COMPLETE BOUGUER
ANOMALY CONTOURS
MULESHOE VALLEY, NEVADA

14 SEPT 81

DRAWING 1


Dse
Dsi
Ou
Dg
MDp
Msw
Mc
Pl
Op
Oe
Pu
Tvb
U
D
COYOTE WASH FAULT
4N-64E-7dc
38° 15'
114° 45'
5000
4000
3000
2000
36
16
34
70
31
14
15
5
41
38



COYOTE WASH FAULT
4N-64E-7dc
38° 15'
114° 45'
5000
4000
3000
2000
1000
Qu
Msw
Dse
Tvb
Op
Oe
Mc

EXPLANATION

U D — FAULTS INFERRED FROM GRAVITY DATA

FAULTS SHOWN ON GEOLOGIC BASE MAP

ALLUVIAL MATERIAL

ROCK (ALL PATTERNS)

CONTOUR INTERVAL = 1000 FT.

DEPTH CALCULATIONS BASED ON DENSITY CONTRAST OF 0.5g cm 3

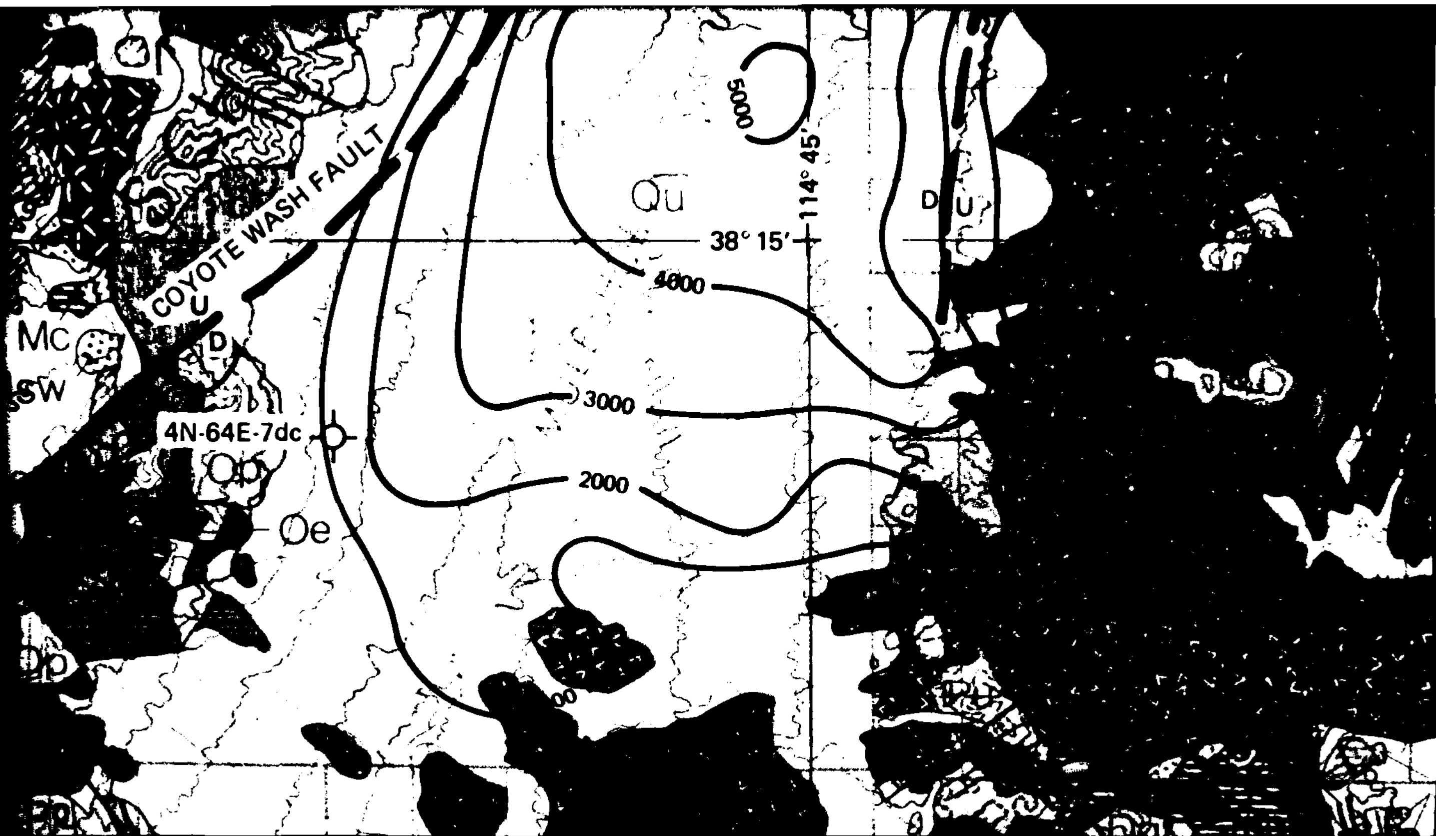
WELL

GEOLOGIC BASE MAP: E. L. Howard (1978)

0

INTERI
MU

14 SEPT 81



ATION

RRED FROM
A

N ON
SE MAP

TERIAL

TTERNS)

ERVAL = 1000 FT.

LATIONS BASED ON
TRAST OF -0.5g cm^{-3}

E MAP: E. L. Howard (1978)

NORTH

SCALE 1: 125,000

0 2 4
STATUTE MILES

0 2 4
KILOMETERS

Ertec
The Earth Technology Corporation

MX SITING INVESTIGATION
DEPARTMENT OF THE AIR FORCE
BMO/AFRCE-MX

DEPTH TO ROCK
INTERPRETED FROM GRAVITY DATA
MULESHOE VALLEY, NEVADA

14 SEPT 81

DRAWING 2

FILMED

8